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INVESTIGATION OF AN ULTRA-FAST ALL-OPTICAL SELF-CLOCKED DEMULITPLEXER

Princeton University

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Terahertz optical demultiplexers are required for ultra-fast time-domain optical switching and processing. This work describes the development of a new interferometric based all-optical switching element that performs this ultra-high bandwidth function. The component is based on a Mach-Zehnder configuration with two spatially offset semiconductor optical amplifiers on the internal arms of the interferometer that act as nonlinear optical elements. This offset and functionality perform the necessary task of optical phase shifting and hence modulation of an incoming optical pulse in a terabit per second data stream in the presence of a counter-propagating clock pulse. Such operation alleviates the need for polarization control and multiplexing or wavelength filtering, which is the basis of previously developed all-optical demultiplexers.

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Abstract

To fully utilize the bandwidth of the optical fiber, high-speed multiplexing and demultiplexing are required. Whereas electronic gates are currently able to achieve speeds of only a few GHz, optical gates can offer speeds in the THz regime, which is commensurate with the bandwidth of the fiber. The key issue to achieve ultra-high processing speeds in optical communications and computing systems is to develop a high-speed optoelectronic or all-optical pulse sampling techniques for high-speed all-optical demultiplexing.

Introduction

Although optical fibers provide the enormous transmission bandwidth required by emerging broadband network and high-performance computing applications, full access to this bandwidth is currently limited by electronic bottlenecks. To fully utilize the bandwidth of the optical fiber, high-speed multiplexing and demultiplexing are required, as well as high-speed routing control and contention resolution in packet-switched systems. Whereas electronic gates are currently able to achieve speeds of only a few GHz, optical gates can offer speeds in the THz regime, which is commensurate with the bandwidth of the fiber. Several key issues must be addressed to achieve ultra-high processing speeds in optical communications and computing systems. In the past year, under this support, we have investigated a new device called a Terabit Optical Demultiplexer (TOD) for high-speed all-optical pulse sampling and demultiplexing, which eliminates key bottlenecks in ultrafast optical systems. This device is self clocking and polarization independent.

This work was performed in close cooperation with Ray Boncek and John Stacy of the Rome Laboratories and the members of the Lightwave Communications Research Laboratory at Princeton University. Our newly proposed device, TOD, consists of a two nonlinear elements, such as semiconductor optical amplifiers, asymmetrically placed in the arms of fiber Mach-Zehnder interferometer, and uses the large but slow resonant optical nonlinearities which all other fast demultiplexers seek to avoid. The TOD functions as a fast gate which uses one pulse to both open and close this gate, with the "ON" time determined by the off-center position of the nonlinear element within both arms. The only

fundamental limit on this device is the decay time of the femtosecond transient nonlinearities which precedes the slower recovering component of an optical nonlinearity.

Experiments and work performed

Through close collaboration with Rome Laboratories during the past year, we have made substantial progress, both experimentally and theoretically, in our investigations of ultrafast optical processing. Our major achievements during the past year are:

Demonstration of the TOD -ultrafast, all-optical, low control energy, single wavelength, polarization independent, cascadable, and integratable switch

Since the observation of large optical nonlinearities in semiconductor material near the resonance regime^{1,2}, all-optical switches based on semiconductor nonlinearities have been investigated extensively^{3,4}. The transition of the optical nonlinearities in the semiconductor by the strong optical pulse is sufficiently fast for ultrafast switching devices. However, the slow recovery time related to interband recombination is a problem for the design of these devices. With the realization of the fast turn-on operation in a GaAs etalon, an additional etalon in series has been used for the ultrafast turn-off operation. With this operation, a switching window of 40 ps has been achieved from etalons exhibiting 30 ns recovery times⁵. Recently this concept has been re-applied to interferometric devices based on the Sagnac and Mach-Zehnder configuration. The first device based on this principle is the terahertz optical asymmetric demultiplexer (TOAD)⁶, and the second is the symmetric Mach-Zehnder (SMZ)⁷. The TOAD used a semiconductor optical amplifier for the nonlinear optical medium, and exhibits 4 ps switching window. The SMZ used GaAs nonlinear waveguides, and exhibits 8 ps switching window. The SMZ has been operated by co-propagating the control and data signal. In this letter, we introduce Mach-Zehnder configuration of the TOAD where control and data signal counter-propagate. The counter-propagation configuration greatly simplifies the separation of the weak data signal from the strong clock signal, therefore an additional filtering optical element is not required at the output. We also use low polarization sensitive semiconductor optical amplifiers for the nonlinear optical media. Therefore, single wavelength, polarization independent operation is possible. Since the nonlinearity is derived from the gain medium, the output data signal can be larger than the input signal permitting cascadability of the data signal. With the

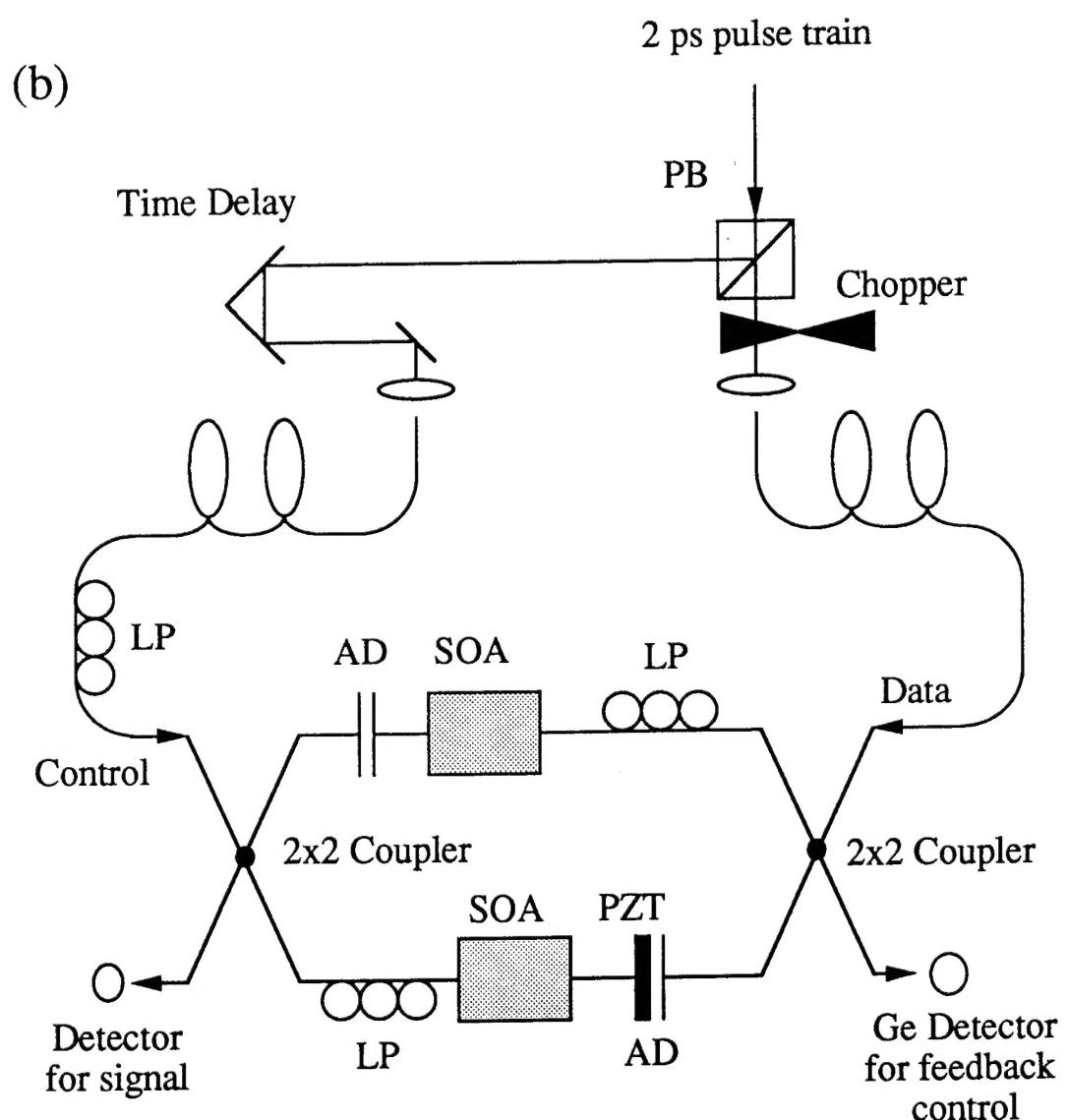
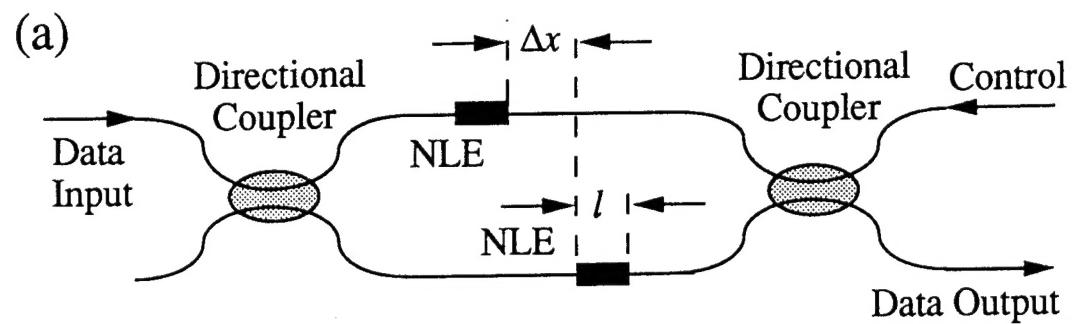
Mach-Zehnder geometry, the device can be made on a small substrate for a small scale integration.

The devised Mach-Zehnder TOAD, shown in Fig. 1(a), is comprised of two directional couplers, and two identical nonlinear optical elements (NOE). The length of two arms inside the Mach-Zehnder interferometer is almost same except for the small optical path length difference that provides a $n\pi$ phase shift between them. Here n is a small integer. The NOEs are placed asymmetrically inside the Mach-Zehnder. This separation distance, Dx , as well as the lengths of NOEs, $2l$, determines the switching window. A data signal launched from the front splits into two at the coupler. The crossover signal experiences additional $\pi/2$ phase shift relative to the straight through signal. Each signal travels through the appropriate arm of the Mach-Zehnder and the nonlinear optical element, and further splits into two by the other directional coupler. At the output of the directional coupler, the signals from the upper and lower arm of the Mach-Zehnder interfere with each other. Without any internal losses, the output signals can be described by

$$I_{out}(t) = \frac{I_{in}}{4} \{G_l(t) + G_u(t) \pm 2\sqrt{G_l(t)G_u(t)} \cos(\phi_l(t) - \phi_u(t))\} \quad (1)$$

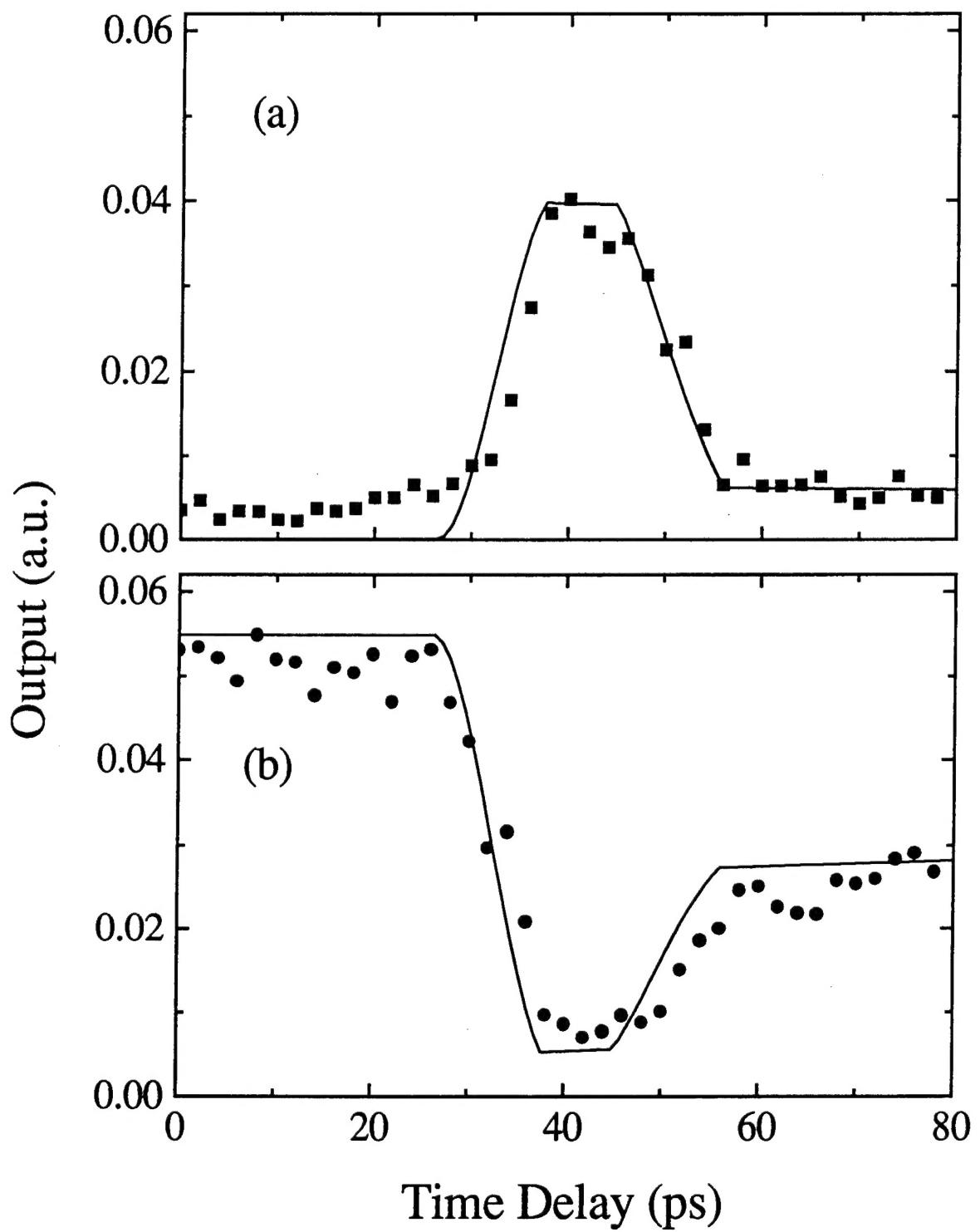
where $I(t)$ is the intensity for the input and the output, $G(t)$ is the gain or loss due to the NOE, and $f(t)$ is the total amount of phase shift by the optical path length from the entrance of the coupler to the exit coupler. The phase shift includes the additional phase shift by the couplers and the NOE. The subscripts l and u denote the lower and upper arm, respectively. $G(t)$ and $f(t)$ are constant if there is no time dependent external influences such as a control optical signal. By adjusting the length of one arm, a complete interference signal at the exit can be achieved - one is destructive and the other constructive. This complete interference can be destroyed by introducing a control signal from the right to change the amplitude and phase of one of two data signals from the left. This causes a switch-on operation. If the control pulse affects the data signal on both arms by introducing negligible difference in the gain and phase, the output signal reverts back to an almost complete interference. This is switch-off operation. The duration of the switching window, depends on the separation distance Dx between the two NOEs, the optical pulse widths and the length of the NOEs. Within the switching window, a part of the data pulse energy can be redirected from the one of the exits to the other.

The experimental demonstration of an optical fiber configuration of this device is shown in Fig. 1(b). Two optical fiber 3dB 2x2 couplers provide splitting, and two semiconductor optical amplifiers provide the necessary optical nonlinearity for switching. The fiber-pig tailed BT&D SOA 3200 semiconductor optical amplifiers are designed for



low polarization sensitivity and operate at $1.3\text{ }\mu\text{m}$. For the demonstration, 2 ps optical pulses are produced by compressing 100 ps optical pulses from a 100 MHz mode locked Nd:YLF laser operating at $1.313\text{ }\mu\text{m}$. The compressed optical pulses are split into two by the polarization beam splitter to provide control and data signals. To determine the switching window, a time delay of the control signal with respect to the data signal is achieved by a stepper motor translator. The control and data signals are coupled into the fibers, and counter-propagate in the Mach-Zehnder. Both signals encounter each other near the SOAs. A fine adjustable time delay element, AD, made out of two GRIN rod lenses with pig-tailed fiber on X-Y-Z translators are inserted on both arms to make the length approximately equal - a few wavelength difference. An ultrafine adjustment required by the interferometer (much less than a wavelength) is accomplished by a piezo-translator on the one of the AD elements. The stability of the fiber optic based Mach-Zehnder has been dynamically maintained by a feed back control system. The computer maximizes or minimizes the control signal output of the Mach-Zehnder by reading a Ge photo-diode output, and controlling the piezo-translator. This dynamic stability may not be required if the length of Mach-Zehnder is sufficiently small. This can be achieved by reducing the length of the fiber and eventually with integration on a small substrate. In this device, two additional loop polarizers, one in each arm, are inserted to rotate the polarization of the data signals. These loop polarizers are also not required if the system becomes small. For the investigation of polarization independent operation of this device, an additional loop polarizer for the control signal before the Mach-Zehnder has been introduced.

The measured result of approximately 20 ps switching window is shown in Fig. 2. Fig. 2(a) is the signal output when the normal output is minimum, and Fig. 2(b) is the signal output when the normal output is maximum. Here normal output means that the output is based on complete interference *i.e.* destructive for minimum output, constructive for maximum output. The x-axis in the graph is the time delay between the control and data signals, and the y-axis is the magnitude of the signal output. The data signal arrives at the SOA ahead of the control signal at the beginning, and the data signal lags the control signal at much later time. This can be seen in Fig. 3(a) with different temporal gains: high gain before arrival of the control pulse and low gain after arrival of the control pulse. The control pulse energy launched into the Mach-Zehnder is about 2 pJ, and the data pulse energy is about 100 fJ. Because of the coupling losses at the various places, the measured control pulse energy right before the SOA is about 0.8 pJ at the upper arm and about 0.5 pJ at the lower arm. By considering additional coupling losses of 3 dB at the SOA interface, the total control pulse energy of about 0.65 pJ at the SOA is used to accomplish the switching. The measured data pulse energy right before the SOA is about 28 fJ at the upper arm and



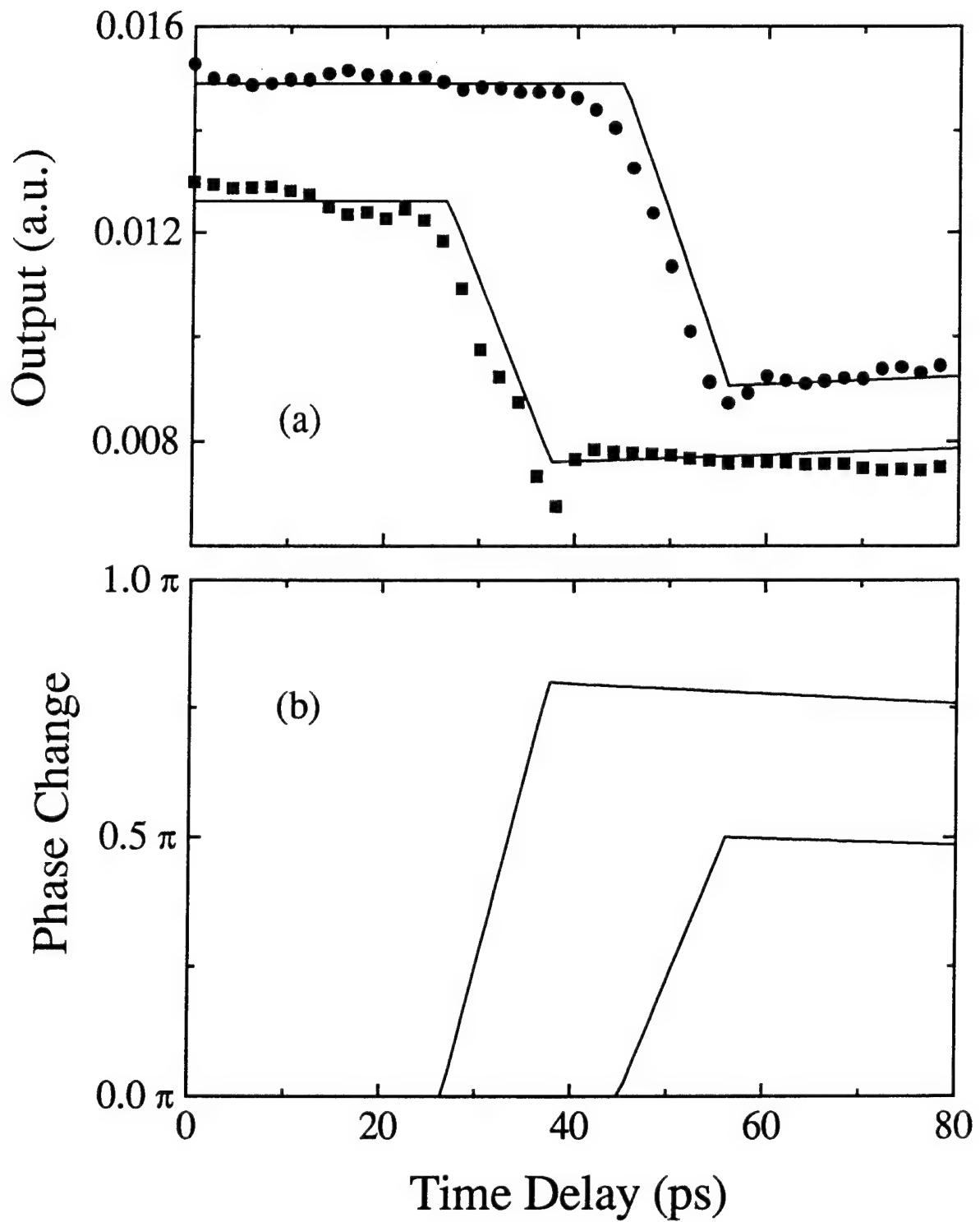
about 33 fJ at the lower arm. With the consideration of 3 dB coupling losses at the SOA interfaces, the total data energy is estimated to be about 31 fJ. The gain characteristics of two SOAs are different, therefore fiber-to-fiber gain of about 2 are obtained by applying 55 mA and 33 mA to the upper and lower SOAs respectively. With a similar experimental condition, a 10 ps switching window has been achieved and is shown in Fig. 4.

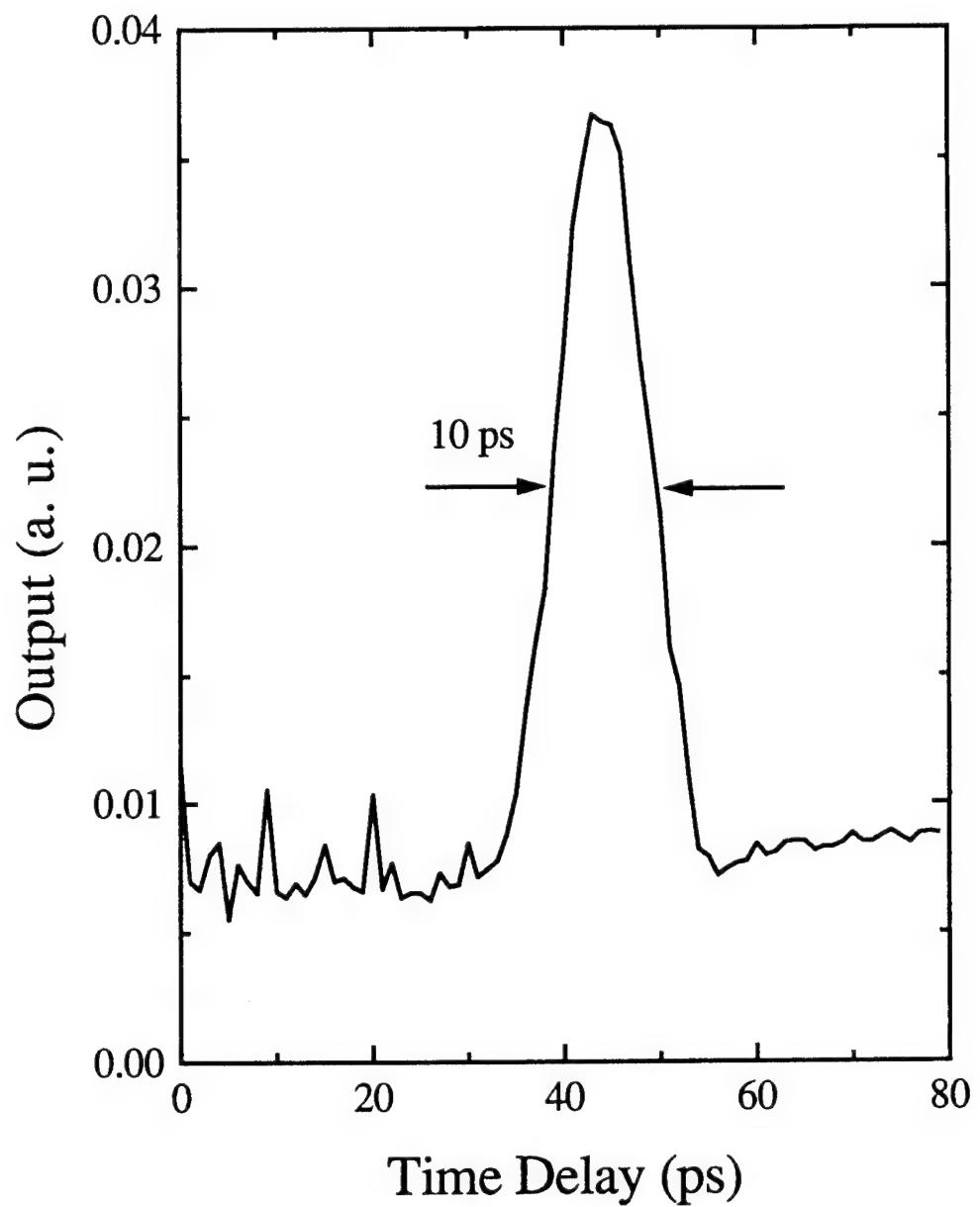
In Fig. 2(a), the data signal output is low when the control signal lags the data signal at both SOAs. The low data signal output changes to high when the control signal in the upper arm arrives at the SOA before the data signal, and the control signal in the lower arm arrives at the SOA after the data signal. This is a fast switching on transition. The switching transition here is about 11 ps and is due to the counter propagation. 11 ps is the twice of the time required for the optical pulse to travel 500 mm length of the InGaAsP SOA which has an index of refraction of about 3.3. This can be seen with the transition period from high gain to low gain in Fig. 3(a). The data signal goes back to low when both control signals pass through both SOAs before the data signals. The switching off transition also depends on the length of the SOA, therefore the switching window is almost symmetrical about the center of the switching window. The similar signal output also has been observed by rotating the control pulse polarization 90 degrees at the input.

The conjugate aspect of the data signal is shown in 2(b). The data signal is high before the first switching transition, and low after the transition. This phenomena is due to two reasons. One is what we already expected from the interferometric device. A part of the signal is redirected to the other exit port. The other reason is due to the gain compression of one SOA but not the other. Before the first switching operation, both data signals experience a high gain. After the switching on operation, one data signal still experiences a high gain but the other experiences gain compression. After the second switching operation, the signal does not revert back to the original signal level. This is due to gain compression by both SOAs.

The gain compression temporal output from the SOAs are shown in Fig. 3(a). High gain persists before the control pulse affects the SOA, and low gain after. At the time of 38 ps and 56 ps for the lower and upper graph, a weak but fast transient gain can be seen at the bottom of the transition. This phenomena is due to two photon absorption and carrier heating effects⁸. The effect of this transient signal disappears after about 2 ps. The longer gain compression recovery is our main interest for the devised switching device. The long recovery time constant is on the order of ns, and is related to the reduction of the carriers by the control pulse.

With the present experimental results of Fig. 2(a) and Fig. 2(b), we can estimate the amount of phase change in both SOAs using Eq. (1). The assumed gain and phase shift





7b

Fig. 4

are shown in Fig. 3 by the solid lines. The expected signal output from the device is shown with the solid line in Fig. 2. The calculated signal output is very close to the experimental results. From the graph of Fig. 3(b), the amount of phase shift is about 0.8 p and 0.5 p. Notice that the 0.5 p phase shift is from the larger gain compression. The difference may be explained by the wavelength used and the gain profiles of the SOA. According to the Kramer-Kronig relationship, the maximum amount of phase shift does not occur at the maximum of gain profile but away from it if the gain profile does not change when the gain compression occur.

In this experimental demonstration, the results shown in Fig. 2(a) before and after the switching are not at zero and not at the same level. This is due to the incomplete interference caused by different amount of coupling losses and gains for the control and data signals due to the adjustable delays and the different gain characteristics of SOAs. For the implementation in the real system with a much slower electro-optic detector to detect the signal, complete interference at switch-off is very important to minimize crosstalk. However this can be easily improved by better matching of the losses and using SOAs with similar gain characteristics. This should not be a problem with an integrated system where the device is built within a small homogenous semiconductor substrate.

Results

During the one-year program on ultrafast all-optical polarization independent demultiplexer we have accomplished the following results:

1. development and demonstration of the TOD (Terabit Optical Demultiplexer) device using a two semiconductor optical amplifiers at 1.3 microns; measure the response time, switching energy, contrast ratio, and inter-pulse crosstalk;
2. performance a hardware simulations of the TOD device to study the time-dynamics of the architecture;
3. study of the new control methods and techniques for implementation; develop techniques to separate the clock and control signals; investigate self-clocking strategies;
4. demonstration of ultrafast (picosecond) time demultiplexing.

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Conclusion

We have developed and demonstrated new ultrafast all-optical polarization and wavelength independent demultiplexer with a 10 ps switching window which corresponds to 100 Gbps. This device has 0.65 pJ of control pulse energy by utilizing a large optical nonlinearity associated with gain compression of the semiconductor optical amplifiers in a counter-propagating Mach-Zehnder configuration. The device has been operated with a single wavelength of $1.313 \mu\text{m}$, but does not require orthogonal polarization between control and data pulses. The estimated phase shift for both SOAs are about 0.8π and 0.5π by 0.40 pJ and 0.25 pJ of control pulse energies. By minimizing the coupling losses, it is possible that the output signal can be larger than the input. This permits the cascadability of the data. The device can also be made by small scale integration.

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